Properties of Magnetohydrodynamic Turbulence in the Solar Wind as observed by Ulysses at High Heliographic Latitudes

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Abstract. The Ulysses mission provides an opportunity to study the evolution of magnetohydrodynamic (MH D) turbulence in pure high-speed solar wind streams. The absence at high heliocentric latitudes of the strong shears in solar wind velocity generally present near the heliocentric current sheet allows investigation of how fluctuations in the magnetic field and plasma relax and evolve in the radially expanding solar wind. We report here results of an analysis of the radial and latitudinal variation of the turbulence properties of the fluctuations, especially various plasma-field correlations, in high latitude regions. The results constrain current theories of the evolution of MHD turbulence in the solar wind. Compared to similar observations at 0.3 AU by Helios, wc find spectra that are similar in having a large frequency band with an f^{-1} power spectrum in the outward traveling component of the waves, followed at higher frequencies (larger wave numbers) by a steeper spectrum. Ulysses observations establish that at high latitudes the turbulence is less evolved than it is in the ecliptic at the same heliocentric distance and this appears to be due to the absence of strong velocity shear. Once Ulysses is in the polar coronal hole, properties of the turbulence appear to be dctcrmincd by the heliocentric distance of the spacecraft rather than by its helio-latitude.

Introduction

Studies of the solar wind during the past two decades have revealed a dynamic and turbulent medium containing hot plasma with twisted magnetic fields [for recent reviews, sec 7'u and *Marsch*, 1995; *Goldstein et al*, 1995a,b]. Understanding how energetic particles propagate through these turbulent magnetic fields, requires a description of both the large-scale structure of the solar wind magnetic field and the three-dimcmional characteristics of the fluctuating magnetic and velocity fields.

It is now clear that the fluctuating solar wind magnetic and velocity fields arc determined in large part by two competing influences, namely, the initial conditions in the solar atmosphere and corona, and the physics controlling the subsequent dynamical evolution in the heliosphere. Conditions in the solar corona are known [*Roberts et al.*, 1992] to be the source of the outward propagating Alfvénic fluctuations observed in the solar wind [*Belcher* and *Davis*, 197 1]. It is also clear [*Roberts et al., 1992*] that, at least near the ecliptic plane, turbulent evolution is driven by velocity shear arising either from the interaction of fast and slow solar wind streams or by the striated structure of the solar atmosphere [Woo, 1995; Woo *and Goldstein,* 1994].

Detailed analyses of plasma and magnetic field data from the Helios and Voyager spacecraft, especially near solar minimum, suggest that in the absence of strong velocity gradients, the evolution of solar wind turbulence is slowed: the degree of Alfvénicity of the fluctuations as determined by the correlation between the fluctuating magnetic and velocity fields (the cross helicity) decreases rapidly with distance when velocity gradients are large [*Bavassano and Bruno,* 1989; *Roberts et al.,* 1987a], but can remain quite large when velocity gradients arc small, even out to 8 or 9 AU [*Roberts et al.,* 1987 b]. Another indicator of turbulent evolution is that the f^{-1} spectrum which characterizes much of the power spectrum of magnetic field fluctuations in the inner heliosphere at low frequencies extends to higher frequencies at larger heliocentric distances when velocity shears are small [*Roberts et al.,* 1991; 1992]. Conversel y, when large velocity shears are pre.sent, an inertial range spectrum of the turbulence, characterized by a well-dcfind~ $^{5/3}$ power spectrum, begins at relatively low frequencies and extends over several decades in frequency.

These analyses have produced a picture of solar wind turbulence which can be tested and refined using data from the unique out of the ecliptic orbit of the Ulysses spacecraft. In addition, several predictions and expectations concerning the nature of the solar wind out of the ecliptic have been described in the literature [*Jokipii and Kóta,* 1989; *Roberts* 1990; *Goldstein et* al. 1995a, b]. In this letter wc report results of an analysis of the radial and latitudinal variation of the turbulence properties of the solar wind at high latitudes, and compare the results both with Helios data and with previous expectations.

Analyses

In this analysis we used a conjoint plasma-magnetic data set at 4 minute resolution. The magnetic field, which is generally available at significantly higher time resolution than is the plasma data, was sampled at the time of the plasma measurement. The plasma data inchrdcd the proton and alpha particle densities, the proton velocity, and the Alfvén speed computed including the measured temperature anisotropies. The intervals we chose were characterized by relatively steady conditions *($V_w \approx 783$* and 754 km/s for the high latitude (2 AU and 4 AU) intervals, respectively) and small velocity gradients. The first interval was DOY 299–312, 1993 after Ulysses had encountered the last evidence of corotating stream interactions on its way *to* high southern latitudes, The spacecraft was near 4 AU and close [o -40° southern latitude. The second interval (DOY 229-292, 1993) was during the maximum southern latitude pass. For comparison with in.ecliptic data that was similarly steady, wc used Helios data obtained in 1978 when that spacecraft was near 0.3 AU.

The data were digitally filtered and decimated to 8 minute time resolution to remove the effects of aliasing apparent in the 4 minute data, The magnetic field data were then converted to Alfvén speed units using the local measurements of the solar wind density corrected for 5% alpha-particles by number, Power spcc tra were computed using fast Fourier transforms.

When dealing with highly Alfvénic turbulence, it is useful to replace the magnetic field and velocity vectors by the Elsässer variables defined by $z^{\pm} = \delta v \pm \delta b$ [*Elsässer,* 1950; 1956], where z^+ and z^- refer to waves propagating "outward" and "inward" with respect to the average magnetic field B_0 and δv and δb arc the fluctuating velocity and magnetic (in Alfvén speed units) fields, respectively. The advantage of using these variables is that for nondissipative and incompressible magnetofluids they are exact solutions of the MHD equations, Because the Reynolds number of the solar wind is a very high and because the wind often behaves quasi-incompressibly, the Elsässer formalism shows the extent to which initially outward propagating Alfvén waves couple to inward propagating fluctuations and other nonAlfvénic disturbances.

Results of the Analyses

In Figure 1a-c wc show power spectra of the Elsässer variables during the two Ulysses time periods analyzed and the interval of Helios data. In all cases, the power in the outward propagating Alfvénic fluctuations, the z^+-power, is the upper curve and the inward propagating Al fvénic fluctuations, the z—power, is the lower curve. The Helios spectrum was constructed from onc hour averages of the magnetic field and velocity data and, therefore, only extends to just above 10-4 Hz in contrast to the two Ulysses spectra **which** were constructed from 8 minute resolution data.

The Ulysses high latitude interval and the Helios interval both have much higher Al fvénicity than does the 4 AU interval; *i.e.* the power in z^+ greatly exceeds that in z^- over much of the frequency range. In addition, at low frequencies, the Helios spectra arc flat to very high frequencies ($>10^{-3}$ Hz), the 2 AU Ulysses spectrum to considerably lower frequency, and the 4 AU spectrum to even somewhat lower frequency (also see, *Horbury et al. [* 1995 a,b]. Onc should also note that in the vicinity of 10^{-4} Hz, the amplitude of the high latitude z^+ spectrum at -2 AU of is -2 times higher than at 4 AU. This is the ratio expected if the fluctuation obey a "WKB" scaling (see, for example, *Heinemann and Olbert [1980]* and *Roberts* [1990]). Similarly, the Helios z^+ spectrum is approximately 6 times higher than the 2AU spectrum over the whole frequency range shown in Figure 1 c, which again reflects a "WKB-like" scaling ($\delta B^2/\rho \propto$ *r-3/r-2).* Note however that work in progress by Balogh et al. investigating radial dependences of fluctuations appears to be finding a radial variation more like a quasi-static solution.

Other interesting aspects of the differences in Alfvénicity between the 2 AU and 4 AU data can be seen by plotting the normalized cross helicity defined by $\sigma_C = 2H_c/E$, where $H_c = 1/2 <\delta v \cdot \delta b>$ and E is the magnetic plus kinetic energy. In Figtn es 2a and b we show $\sigma_c(k)$ for those two intervals. In addition to $\sigma_c(f)$, the plots include $\sigma_{cr}(f)$ and $\sigma_{c\perp}(f)$, calculated from the radial and transverse components of E and H_c. Note that at 2 AU, $\sigma_c(f)$ is very close to unity (more Alfvénic). Of particular interest is the fact that the low values of $\sigma_c(f)$ below 10^{-6} Hz reflect drc sharp decline in $\sigma_{cr}(f)$. The transverse components $\delta v_\perp$ and $\delta b_\perp$ are. still highly correlated, suggesting that quasi-planar Alfvénic fluctuations still dominate below 10^{-6} Hz. Because Alfvénic fluctuations are not expected to propagate at such low frequencies, it is possible that spacecraft motion across field lines in the corotating fı amc is aliasing high frequency Al fvénic fluctuations into the observed time series at lower frequencies. Note that the high Alfvénicity at large scales implies that the convergence of z^+ and z^- spectra at low frequencies is duc entirely to variations in the radial velocity sampled as Ulysses crosses field lines. By 4 AU $\delta v_\perp$ and $\delta b_\perp$ arc relatively uncorrelated. In fact, there is a general decay in Alfvénicity with distance across the entire frequency band.

Another quantity from which turbulent evolution can be deduced is the spectrum of the Alfvén ratio, defined as the ratio r_A between kinetic energy and magnetic energy. The importance of this quantity arises from the Alfvén effect first described by *Kraichnan [1965]*. Kraichnan's prediction was that rhc magnetic and kinetic energy (per unit wave number) in an incompressible turbulent magnetofluid should be equal, on average, in the inertial range. As shown in Figure 3, r_A is approximately 1/2 for both the 2 and 4 AU intervals. As wc discuss below, the Alfvén ratio as measured in the solar wind is rarely found equal to 1 as predicted. The explanation for this discrepancy is not known. The component energy ratios plotted in Figure 3 also show that $r_{A\perp}$ remains -1/2 back to below 10^{-6} Hz, consistent with the high Al fvénicity of $\delta v_\perp$ and $\delta b_\perp$ at those scales.

Discussion and Conclusions

The most obvious characteristic of the power spectra of the high latitude Ulysses data is the relatively slow turbulent evolution evident, especially when compared with in-ecliptic observations at comparable radiaf distances, Whereas by 2 AU in the ecliptic the cross helicity generally shows a significant reduction from its highest values [*Roberts et al.* 1987a,b], the values measured by Ulysses arc of order 0.8 (compare Figure 2a). That a significant percentage of the fluctuations between 10^{-5}-10^{-3} Hz arc outward propagating and highly Alfvénic, is also evident from Figure lb. The low frequency results for $\sigma_{c\perp}(f)$ and $r_{A\perp}(f)$ shown in Figures 2 and 3, suggest that longitudinal sampling of Alfvénic fluctuations as Ulysses crosses field lines may account for the apparent presence of such fluctuations at frequencies well below the regime in which they arc thought to propagate. By 4 AU, however, the Alfvénicity of the transverse fluctuations in the 10^{-6}–10^{-5} Hz band has decreased markedly, indicating the possibility of dynamical evolution.

Another indication of the slow rate of turbulent evolution in the high latitude Ulysses data is that the f^{-1} portion of the spectrum, which dominates the low wave number, large spatial scales, extends to relatively high frequencies (-10^{-4} Hz) (Figure 1 b), whereas, in the ecliptic near 1 AU, the flat f^{-1} spectrum ends closer [o 10-5 Hz [*Matthaeus and Goldstein*, 1982b], except in the most Al fvénic regions. The frequency at which the spectral breakpoint changes from f^{-1} at low frequencies to the $f^{-5/3}$ in the inertial range moves [o progressively lower frequencies with increasing heliocentric distance [see also *Horbury et al.*, 1995c]. This evolution is rapid in the imcr heliosphere, as can be seen most clearly in Helios data [*Bavassano et al., 1982]*. Beyond 1 AU the evolution in the breakpoint is much slower and less obvious [*Burlaga and Goldstein*, 1984; *Goldstein et al., 1984; Klein et cd., 1992].*

Evidence for turbulent evolution by 2 AU is found in the spectral evolution seen in Figure 1, Also, highly Alfvénic Helios data do show $r_A(f) \approx 1$ near 0.3 AU, bor $r_A(f) \approx 0.5$ by 1 AU [*Goldstein et al.*, 1995a], suggesting evolution from a nearly equipartitioned state to onc in which magnetic energy dominates. As noted above, the theoretical expectation is for $r_A(f) \approx 1$. Equipartition has been reported in two-dimensional simulations [*Fyfe and Montgomery*, 1976], but solar wind observations most often show average values of $r_A(f)$ in the inertial range close to 0.5 *[Roberts et cd.,* 1987a,b; 1990; 1992; *Matthaeus et al.* 1982a; *Rob-*

erts, 1992]. However, *Goldstein et al. [1995c]* have suggested that the pressure anisotropy of pickup ions may act in some circumstances to reduce r_A.

Comparison of the intensities of the *power* spectra in Figure 1 at 0.3 (Helios) and Ulysses at 2 and 4 AU suggests that the scaling of the z^+ amplitudes with distance satisfies WKB-scaling at 10^{-6} Hz, *i.e., the* power is expected to decrease as $1/r$ *[Heinemann arrd Olbert, 1980]* for magnetic field in Alfvén speed units. The observed change in power between 2 and 4 AU is approximately a factor of 2. While this dependence is generally expected in the inertial range, *Jokipii arrd Kota [1989]*, noting that the polar magnetic fields would be radial, predicted no fall-off with radial distance of B (in Alfvén speed units). *Roberts [1990]* argued that the effects of turbulence would cause the variation with distance to follow the WKB-scaling. The linear scaling argument of *Jokipii and Kóta [1989]*, when applied to velocity fluctuations, predicts that r_A would approach O as $1/r^2$ ($\rho \delta v^2 \propto 1/r^4$), which is not observed. It must bc noted, however, that *Jokipii et al. [1995]* have. analyzed the variation in the variance of the magnetic field over the range 1.5-4 AU and concluded that the variation fits their expectations. The addition of data from 1.5-2 AU, which is not included here, contributes significantly to their conclusions. Work in progress by Balogh et al. on the radial dependence of the low frequency fluctuations finds a low frequency variation for the variance of roughly r^{-22} (preliminary results) at frequencies of about 3 10^{-6} Hz (i.e., slower decrease than WKB-like). Furthermore, the variations of and correlations with velocity were not addressed in these works. The apparent difference in radial variation at low frequencies between our results and those just quoted requires further investigation.

Wc conclude that the observed evolution of the magnetic and velocity fields between 2 and 4 AU at high latitudes appears consistent with previous expectations derived from in-ecliptic studies and from numerical simulations [*Roberts, 1990; Roberts et al., 1991;* 1992]. The evolution of the turbulence is less evolved than at corresponding distances in the ecliptic duc to the absence of large-scale velocity gradients. The low frequency results ($f < 10^{-5}$ Hz) may be duc to sampling of features in longitude, and the extent to which spatial versus temporal fluctuations contribute to this frequency regime needs further investigation.

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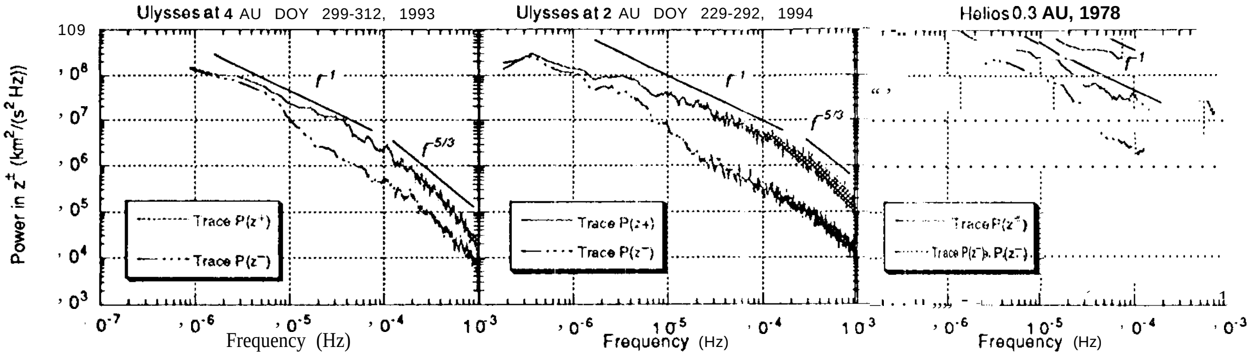

Figure 1, Trace of the power spectrum of the outward propagating (z^+, upper curve) and inward propagating (z-, *lower curve)* Alfvénic fluctuations; (a) for a 13 day period while Ulysses was at approximately 4 AU; (b) for a 63 day period while Ulysses was at high southern latitudes and a radial distance of approximately 2 AU; and, (c), similar to (a), but for a period during 1978 when Helios was near 0.3 AU.

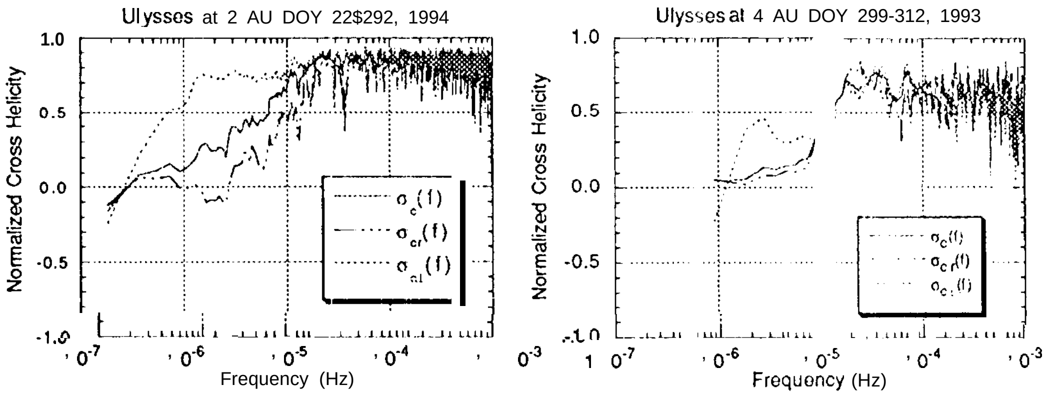

Figure 2. The normalized cross helicity $\sigma_c(f)$ calculated from the trace of the power spectral densities of z^* and the radial and transverse normalized cross helicities computed from the radial and transverse components of $z^{\pm}$, (a) for the 2 AU Ulysses interval, and (b), for the 4 AU Ulysses interval.

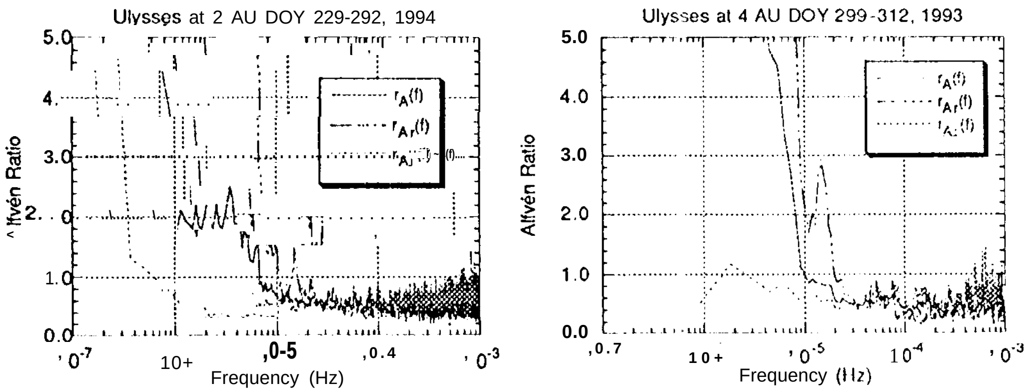

Figure 3. The spectrum of $r_A(f)$ calculated from the trace of the power spectral densities of $z^{\pm}$ and the radial and transverse ratios of kinetic and magnetic energy computed from the radial and transverse components of z*; (a), for the 2 AU Ulysses interval, and (b), for the 13 day interval while Ulysses was at approximately 4 AU.